RI 9003

RI 9003

Bureau of Mines Report of Investigations/1986

Large-Scale Laboratory Drag Cutter Experiments in Hard Rock

By R. J. Morrell, D. A. Larson, and D. E. Swanson

UNITED STATES DEPARTMENT OF THE INTERIOR

Report of Investigations 9003

Large-Scale Laboratory Drag Cutter Experiments in Hard Rock

By R. J. Morrell, D. A. Larson, and D. E. Swanson

UNITED STATES DEPARTMENT OF THE INTERIOR
Donald Paul Hodel, Secretary

BUREAU OF MINES
Robert C. Horton, Director

Library of Congress Cataloging in Publication Data:

Morrell, Roger J

Large-scale laboratory drag cutter experiments in hard rock.

(Report of investigations / Bureau of Mines ; 9003)

Bibliography: p. 13.

Supt. of Docs. no.: I 28.23: 9003.

1. Drag bits (Drilling and boring)—Testing. 2. Mining machinery. 3. Rock mechanics. I. Larson, David A. II. Swanson, David E. III. Title. IV. Series: Report of investigations (United States. Bureau of Mines) ; 9003.

TN23.U43 [TN281] 622s [622] 85-600244

CONTENTS

ILLUSTRATIONS

TABLES

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot	in/s	inch per second
ft^3	cubic foot	$(in \cdot lb)/in^3$	inch pound per cubic inch
ft/s	foot per second	lb	pound
g/cm^3	gram per cubic centimeter	lb/in^2	pound per square inch
in	inch	pct	percent
in^3	cubic inch	st	short ton
in/lb	inch per pound		

LARGE-SCALE LABORATORY DRAG CUTTER EXPERIMENTS IN HARD ROCK

By R. J. Morrell,[1] D. A. Larson,[2] and D. E. Swanson[2]

ABSTRACT

The Bureau of Mines conducted a series of laboratory experiments to test a cutting technique for hard rock using large-scale drag cutters. Cutting experiments were performed on rocks ranging in compressive strength from 10,000 to 27,000 lb/in^2, using large drag cutters from 3 to 6 in. in width. The tests were conducted on a special test apparatus, called a ripper tester, which made a curvilinear cut across the rock sample while measuring the cutting force acting on the drag cutter. The cutting method that evolved from these experiments is called ripper cutting, and its energy efficiency appears superior to all other large-scale mechanical fragmentation techniques. In addition, the method created very little dust, and the wear on the bits was negligible.

A fragmentation system based on ripper cutting was then devised, and a large-scale test device was fabricated to allow full-scale laboratory testing of the system. The results of these tests will be published in future Bureau reports.

[1]Supervisory mining engineer.
[2]Mining engineer.
Twin Cities Research Center, Bureau of Mines, Minneapolis, MN.

INTRODUCTION

BACKGROUND

The most basic activity of any mining operation is the cutting of the ore away from the surrounding rock. In the vast majority of underground mining operations, this cutting or fragmentation process is accomplished by drilling and blasting. The drilling and blasting method, however, suffers from several significant deficiencies that prevent any major improvement in the process. The most serious problem is that the process is cyclic, with a series of mutally exclusive operations (i.e., drilling, blasting, mucking, etc.) that prevent the process from being continuous. The cyclic process requires more expensive batch handling systems and precludes the use of cheaper, more efficient conveyor haulage at the face. In addition, blasting creates problems with oversize material, damages the back and ribs, which require additional scaling and support, and creates noxious fumes and dust that pollute the mining environment.

The Bureau of Mines has long recognized the benefits of continuous nonexplosive excavation for hard-rock underground mines and has initiated a program to find a simple but efficient way to fragment hard rock mechanically, which could be used to extend the application of mechanical mining machines into hard rock. The application of a successful fragmentation technique would change hard-rock mining the same way the continuous miner changed underground coal mining. There have been many attempts to produce a machine, but the problem has always been the lack of a suitable fragmentation technique around which to construct the machine.

In studying past efforts, the Bureau concluded that most past development had taken place without a thorough understanding of what the hard-rock mining industry required from such a mining machine. Thus, the Bureau's first effort was to define industry's needs in terms of cost, productivity, versatility, maneuverability, etc. Although the industry's needs are diverse because of the many different mining methods being used, the predominant fragmentation technique is drilling and blasting. Thus, if the advantages of drilling and blasting in development and stoping operations could be specified accurately, they would define the performance goals that a mining machine would have to meet or exceed to be of any use to the mining industry.

An assessment was therefore conducted of drilling and blasting, using data from a wide variety of sources. It showed that the drill-blast method had the following general performance characteristics:

1. It can break any materials from very soft to very hard;
2. It works in any condition including high water inflows, blocky ground, mixed face, etc.;
3. It can excavate any size or shape of opening;
4. It can negotiate sharp turns and steep grades;
5. It achieves relatively high production at relatively low cost;
6. It produces a wide range of fragment sizes, which affect the applicability and efficiency of the muck haulage system; and
7. The cost to fragment a ton of ore varies with the strength of the rock and the size of the opening.

Costs were estimated for a wide range of sizes and rock strengths so that accurate comparisons could be made for a variety of conditions (1).[3] As an example, the cost to drill and blast only in medium-strength rock (30,000 lb/in^2) is calculated at \$2.60/st for a 10- by 10-ft heading and \$1.91/st for a 10- by 20-ft heading.

[3] Underlined numbers in parentheses refer to items in the list of references preceding the appendixes.

These performance characteristics of drill and blast excavation (items 1 through 7 above) were then defined as the goals that must be matched or exceeded by a successful mechanical miner.

Once the performance goals were clearly defined, project personnel began to analyze all known methods of excavation to determine the limits and capabilities of each and their ability to meet the performance goals. The analysis included tunnel-boring machines, roadheaders, continuous miners, raise drills, impactors, saws, and rotary drills such as tricone, diamond, and auger. As expected, no current or experimental methods could be found to satisfy all of the performance goals. The problem was either the inability of the cutters to fragment hard rock, or if the rock could be cut, the inability to fragment it economically. Once it was clear that no off-the-shelf solution existed to fragment rock efficiently or economically enough to compete with drill and blast fragmentation, a research program was initiated to devise such a fragmentation system.

Fortunately, a previous study of drag cutting in hard rock had identified a concept that promised to meet the requirements of such a fragmentation system. This concept was called ripper cutting.

RIPPER CUTTING CONCEPT

The concept of ripper cutting was devised from observing kerf cutting experiments with drag cutters at the Bureau's Twin Cities Research Center (5). The experiments were conducted in an abrasive dolomite (27,000-lb/in^2 compressive strength) using 1/2-, 1-, and 1-1/2-in-wide bits and cut depths of up to 1 in. While these experiments were concerned with cutting kerfs, it was observed that the cutting process improved significantly if certain conditions were met:

1. Surface cuts were up to five times more efficient than confined deep kerf cuts;
2. The use of the last cut as an additional free face also improved efficiency by up to five times; and
3. The process was most efficient when the cross-sectional area of the cut was largest and the depth of cut was limited to one-third to one-half the width of the cut.

Using these results as the underlying principles of operation, a method of fragmentation called ripper cutting was devised (fig. 1). Ripper cutting is defined in this report as a cutting method that uses a single, large drag cutter to make slow, deep, vertical cuts on the surface of the rock and uses the last cut as an additional free face. The path of the cutter can be either linear or curvilinear as required. The experimental program described in the following sections was designed to test this cutting concept in a variety of rocks and to compare its efficiency with that of other mechanical fragmentation methods.

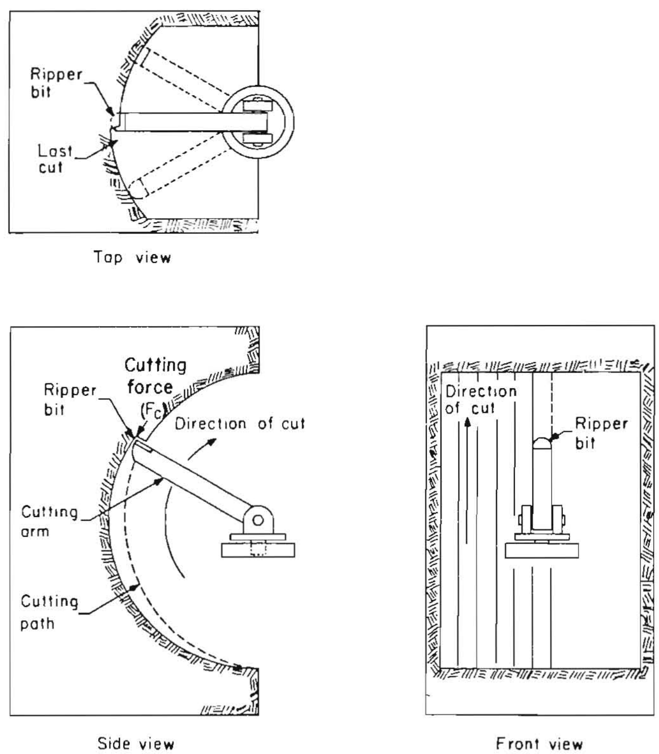

FIGURE 1. - General concept of ripper fragmentation system.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

ROCKS TESTED

Four rocks, which ranged in compressive strength from 10,000 to 27,000 lb/in^2, were tested (tables 1-2). These rocks were considered to be relatively homogeneous except for the Kasota stone, which had a distinct bedding plane. Every attempt was made to orient the internal structure to simulate horizontal bedding and a vertical cutting depth. Rock samples were wire-sawed into 2-ft cubes for the cutting tests.

RIPPER CUTTERS

The drag cutters used in these experiments were specially designed and constructed of tool steel and heattreated to a hardness of 58 to 60 Rockwell C. All bits had a center thickness of 1 in, and each had three holes for attaching to the bit holder. The bits were constructed in the crown style, the wedge style, and the modified crown style. The wedge bits were constructed only in a 3-in width, the modified crown bits only in a 4-1/2-in width, and the crown bits in a 3-in and a 6-in width. The wedge bits and modified crown bits were constructed with 0° rake angles, while the crown bits were constructed with -10°, 0°, and +10° rake angles. The bit styles tested are shown in figure 2.

RIPPER TESTER

The ripper cutting experiments were performed on a special Bureau-designed test apparatus called a ripper tester (fig. 3). This device was designed to cut a curvilinear path through the rock under test. The cutting path was a 65° segment of a circular arc. The motion was developed from a 2-ft-long cutting arm, pinned at one end to allow it to swing through an arc. The cutting arm was powered by extending a hydraulic cylinder, and the measurement of the hydraulic pressure in this cylinder gave a measurement of the cutting force on the cutter. This device could generate a

TABLE 1. - Rocks tested

Commercial name	Geologic name	Locality
Indiana limestone (type 1).......	Salem Limestone...................	Bedford, IN.
Kasota stone (limestone).........	Oneota Member, Prairie du Chein Formation.	Kasota, MN.
Tennessee marble.................	Holston Limestone.................	Knoxville, TN.
Valders white rock...............	Cordell Dolomite Member, Manistique Formation.	Valders, WI.

TABLE 2. - Physical properties of rocks tested

Property	Indiana limestone	Kasota stone	Tennessee marble	Valders white rock
Compressive strength..............lb/in^2..	9,991	13,184	16,809	27,230
Tensile strength..................lb/in^2..	502	792	1,219	793
Shore hardness..........scleroscope units..	32	37	55	68
Apparent density...............$slugs/ft^3$..	4.635	4.818	5.186	5.056
Do...........................g/cm^3..	2.395	2.487	2.681	2.613
Static Young's modulus.........10^6 lb/in^2..	4.4	5.7	9.0	5.7
Longitudinal velocity................ft/s..	14,610	17,119	20,058	12,815
Bar velocity.........................ft/s..	12,007	14,708	16,845	12,118
Shear velocity.......................ft/s..	8,489	9,360	10,590	8,513
Dynamic Young's modulus........10^6 lb/in^2..	4.65	7.42	10.29	5.17
Poisson's ratio...........................	0.33	0.28	0.32	0.20
Shear modulus..................10^6 lb/in^2..	2.32	2.90	4.07	2.55

cutting force of 100,000 lb and a cutting speed of 1 in/s. The cutting speed was low, but most researchers conclude that speed has no major effect on cutting force (3, 6). The side and normal components of the cutting force were not measured during these tests because of the complexity of the instrumentation required and time constraints. These force parameters will be measured in future tests.

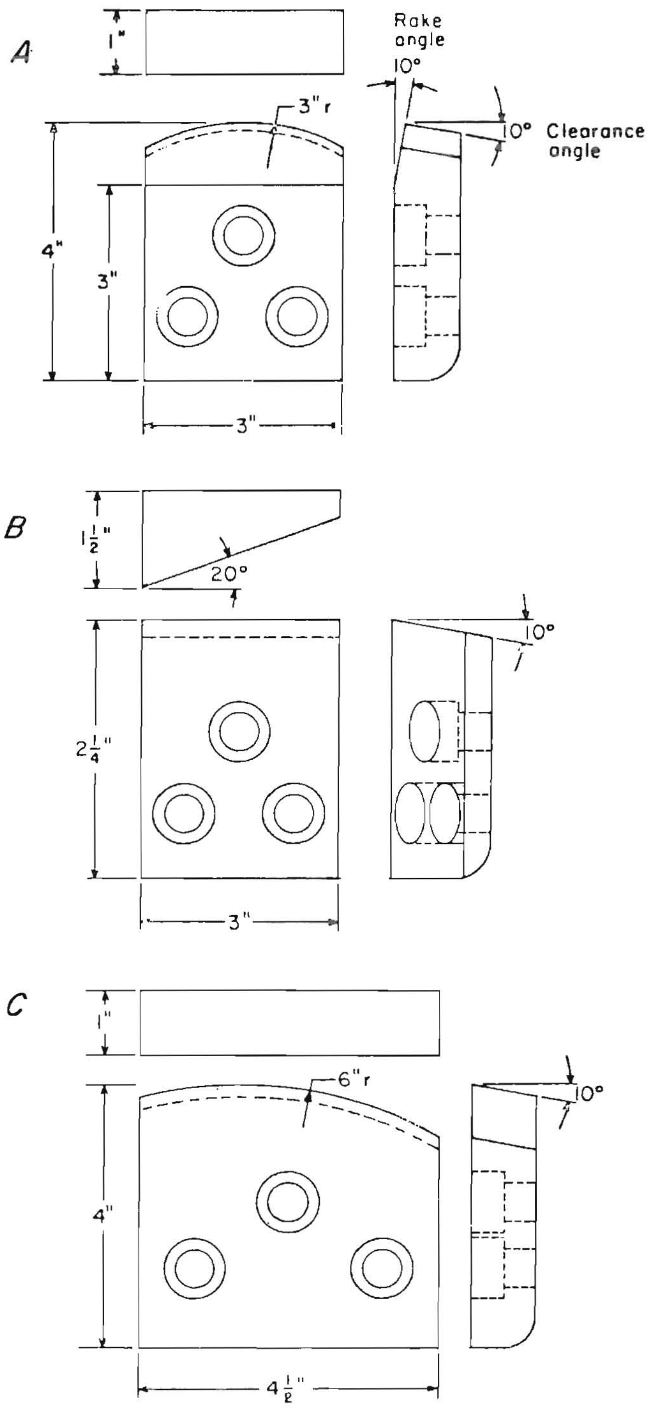

FIGURE 2. - Ripper bits tested. *A*, Crown bit; *B*, wedge bit; *C*, modified crown bit.

CALCULATION OF BIT EFFICIENCY AND CUTTING FORCES

The following factors were used to determine cutter efficiency: the energy consumed, the smoothness of the cutting process, the wear on the bit, and the dust created during cutting. As the test program proceeded, it was apparent that cutter wear and dust levels were very low, and thus they were not recorded for the remainder of the program. For example, the wear on the bits involved only a slight rounding of the cutting edge and some polishing of the other cutting surfaces. The dust levels generated were very small, as no dust was visible to the unaided eye. In later full-scale tests, the dust and wear data might achieve some practical significance and they will be measured and recorded.

The efficiency of the cutting process based on energy consumed was calculated for these tests. To take into account the hardness of the rock being cut and

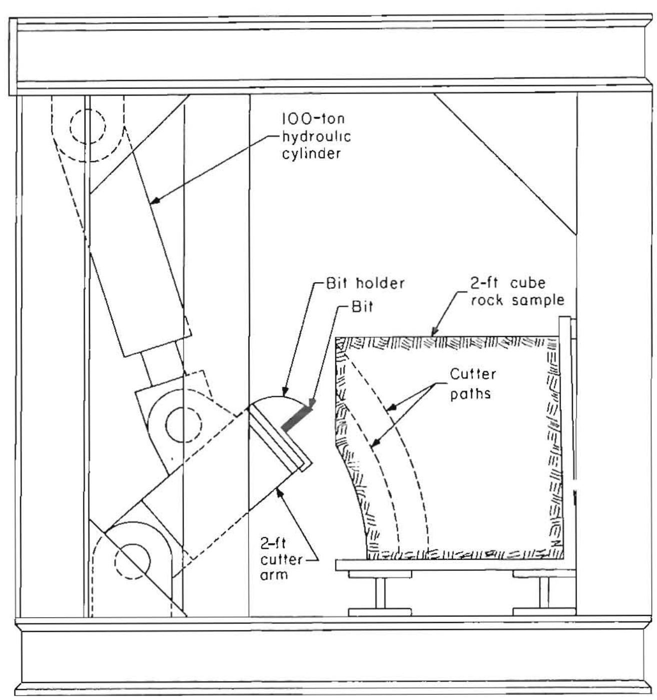

FIGURE 3. - Ripper tester.

the amount of rock being cut, a method of measuring efficiency described by Hughes (4) and Gaye (2) was used. This efficiency parameter, called rock number (N_R), is defined as follows:

$$N_R = \frac{\sigma_c}{E_s},$$

where N_R = rock number (dimensionless),

σ_c = unconfined compressive strength of rock being cut, lb/in^2,

and E_s = specific energy of the process, which is calculated as the energy consumed (in·lb) divided by the volume of cuttings produced (in^3), which yields (in·lb)/in^3.

Note that E_s in inch pounds per cubic inch reduces to pounds per square inch so that N_R becomes dimensionless, and the larger the N_R the more efficient the process. For comparison, N_R values given by Gaye and some calculated by the Bureau for a variety of mechanical fragmentation systems are shown in table 3. The N_R values given in table 3 were calculated using the energy actually supplied to the bit. They do not include the energy lost in the mechanical and electrical mechanisms that power the bit. This should be kept in mind if comparisons are to be made between the E_s and N_R values given in this report and those of other researchers.

The other cutting parameters of interest were the average cutting force and the peak cutting force. The cutting of rock with a drag cutter is a discontinuous process that involves the formation of a series of discrete chips. The chipping process begins as the bit contacts the rock and the force on the bit begins to rise. The force continues to rise until a chip is formed in front of the bit. The cutting force then drops rapidly to a low value until the bit again contacts the rock. This cycle repeats itself throughout the cut so that a recording of cutting force appears as a series of sharp waveforms. The average force parameter is, therefore, only a convenient means of calculating the average energy used in the rock cutting process. The average cutting force is calculated by dividing the area under the force curve by the length or time of the run.

Peak cutting force is the maximum force required to form a rock chip. The value of peak force also varies because the rock chips formed are of different sizes and shapes, each requiring a different level of cutting force. Peak force was subjectively defined as the average of the three highest peak forces experienced in each run, which gave a more consistent value for peak force than just measuring the highest peak force. A sample size of three was selected as the best compromise because a larger size seriously biased the average value in the lower direction, while a sample of fewer than three did not give consistent results.

TABLE 3. - Rock numbers for some mechanical excavation techniques

Excavation technique	Rock number (N_R)
Measured at Bureau of Mines:	
1- to 3-in-diam diamond drill	0.01-0.05
1- to 3-in-diam pneumatic percussive drill	.6 - .9
12-in-diam tricone bit	1.8
Single disk cutter	1.5 -2.2
1/2-in drag cutter	2.8
From Gaye (2):	
40-in milled tooth cutterhead	1.75-2.5
Tunnel-boring machine with disk cutters	4 -6
Roadhead excavators	8

RIPPER CUTTING TEST PROGRAM

EXPERIMENTAL DESIGN

The objectives of this experimental program were to test the ripper cutting concept in a variety of rocks with a variety of cutting tools and to compare the results with those of conventional mechanical fragmentation systems. The following independent variables were considered to be of primary importance in these experiments: the shape and size of the bit, the cutting angle of the bit, the width and depth of cut, and the size of the cut. The measured or dependent variables were the average cutting force, the peak cutting force, and the specific energy. Each of these parameters is discussed in turn in the following sections.

TYPICAL CUTS AND FORCE RECORDINGS

All cuts in these experiments were made on a curvilinear path of 2-ft radius with cut lengths that ranged from 1 to 2 ft. All cuts were spaced to use the last completed cut as the free face, and all cuts were surface cuts. Some typical cuts in a 2-ft block of Indiana limestone are shown in figure 4.

The cutting force (F_c) acting on the bit was measured and recorded during these experiments. A typical force recording is shown in figure 5. (Note the concept of average force and peak force.) The normal (F_n) and side (F_s) components of force acting on the bits were not measured during these experiments because of

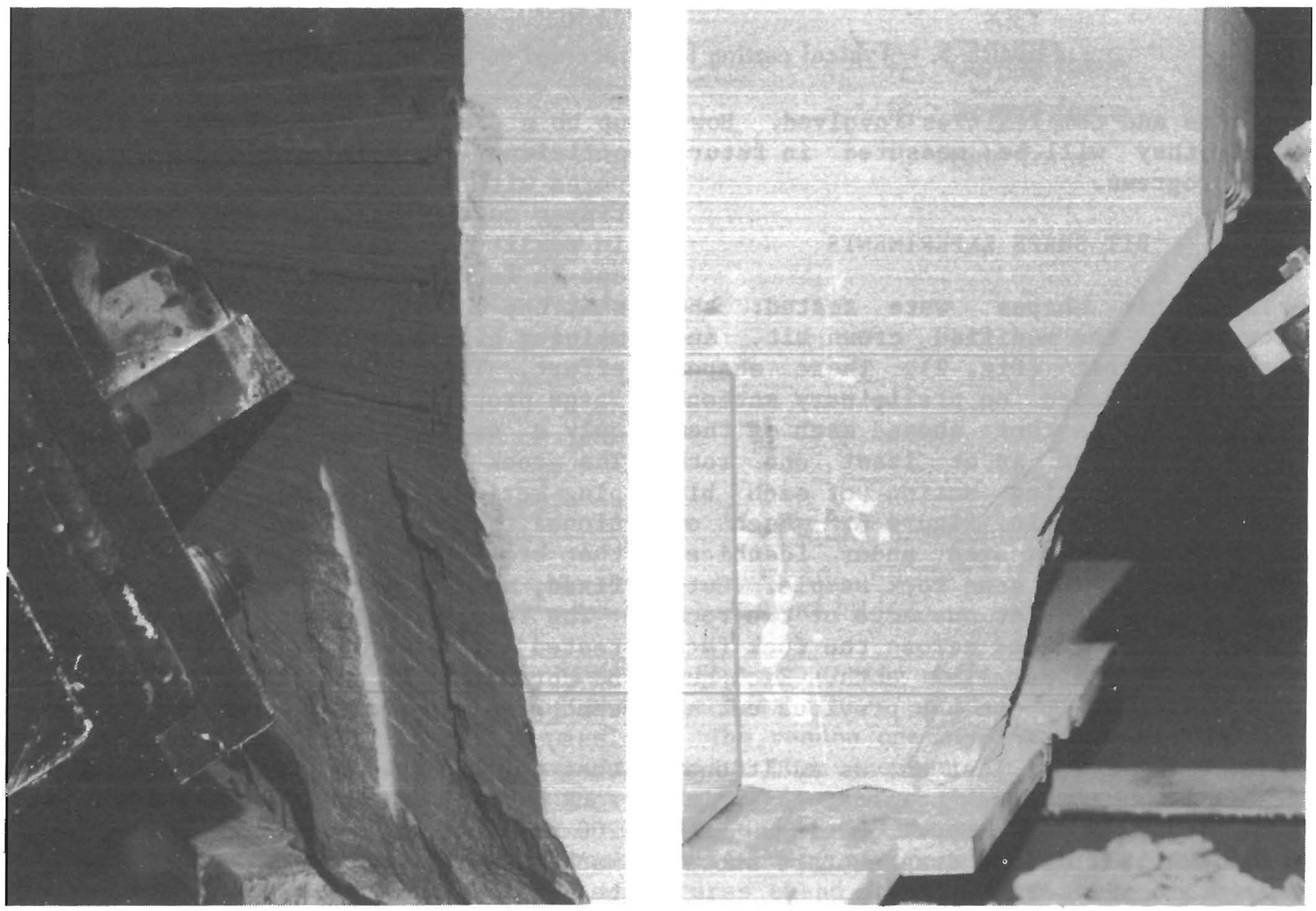

FIGURE 4. - Typical ripper cutting in Indiana limestone with wedge bit.

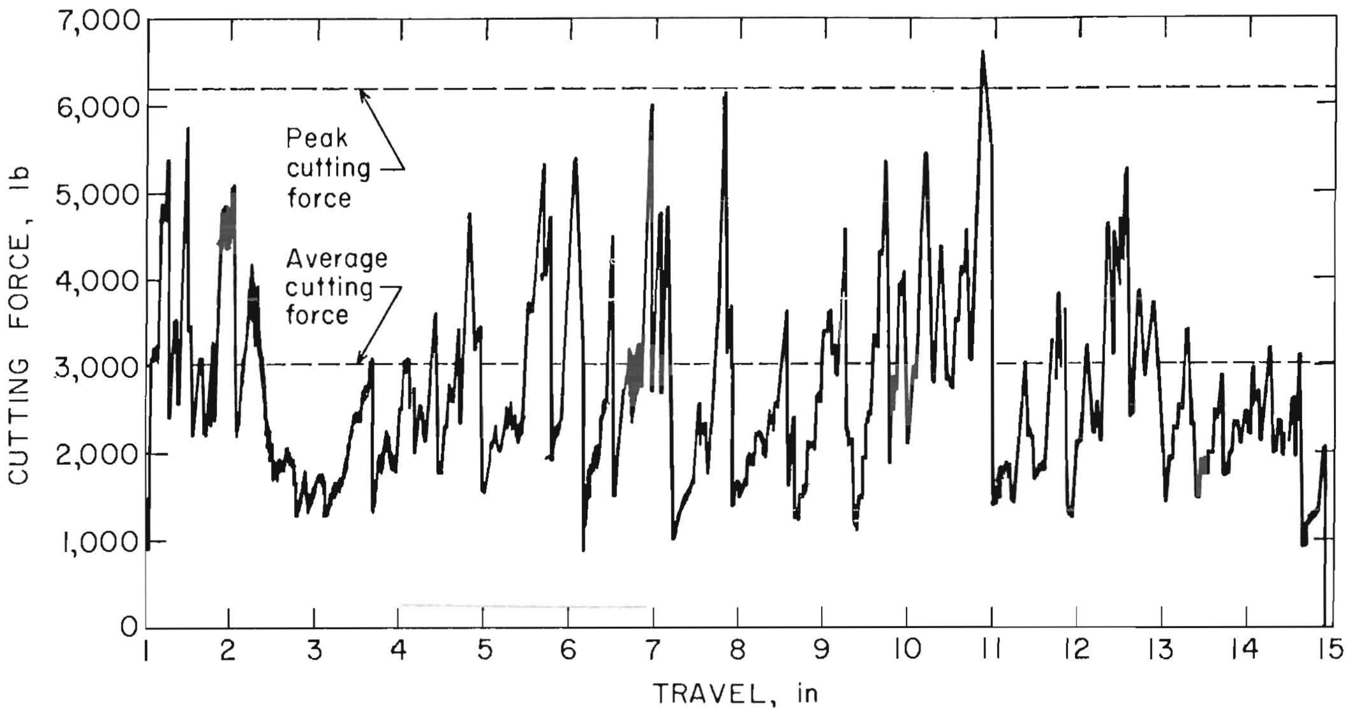

FIGURE 5. - Typical cutting force recorded during ripper cutting.

the time and complexities involved. However, they will be measured in future test programs.

BIT SHAPE EXPERIMENTS

Three bit shapes were tested: the crown bit, the modified crown bit, and the wedge bit (fig. 2). These shapes were chosen based on preliminary screening experiments that showed each of them to be effective in at least one rock type. The cutting action of each bit type is shown in figure 6.[4] Each of these bits was tested under identical conditions in the same rock sample. Cutting always began at one edge of the rock sample and proceeded across the rock face in a series of parallel cuts. Each cut was positioned to use the previous cut as an additional free face.

The use of the last cut as additional free surface to break towards is an important feature of ripper cutting. Previous work with small drag cutters showed up to a 500-pct improvement in cutting efficiency with this technique as compared with an unrelieved cut. While the ripper cutter cuts all rock in its path, in reality the majority of rock is broken out in large pieces ahead of the bit so that the cutter only smooths out the remaining high points of rock with little effort. This cutting action produces a large proportion of large rock chips and only a small volume of fines and dust. The rock broken by the improved chipping action that occurs with this additional free face is analogous to the rock that breaks out between the cutters on a fixed, multipick cutterhead.

The results for the three bit shapes tested are shown in table 4. It should be noted that no attempt was made to test each bit in every rock type. Nevertheless, the results are sufficient to show that the best energy efficiency in each rock tested (N_R = 9.0 to 12.7) is 50 to 200 pct better than for tunnel-boring machines (N_R = 4 to 6) and 12 to 58 pct better than for roadheaders (N_R = 8) (table 2). While roadheaders are more efficient than tunnel-boring machines, they are limited to cutting rock of about 12,000 lb/in^2 or less. Thus, the ripper

[4]Normal and side forces are shown in figure 6 for completeness although they were not measured during these experiments.

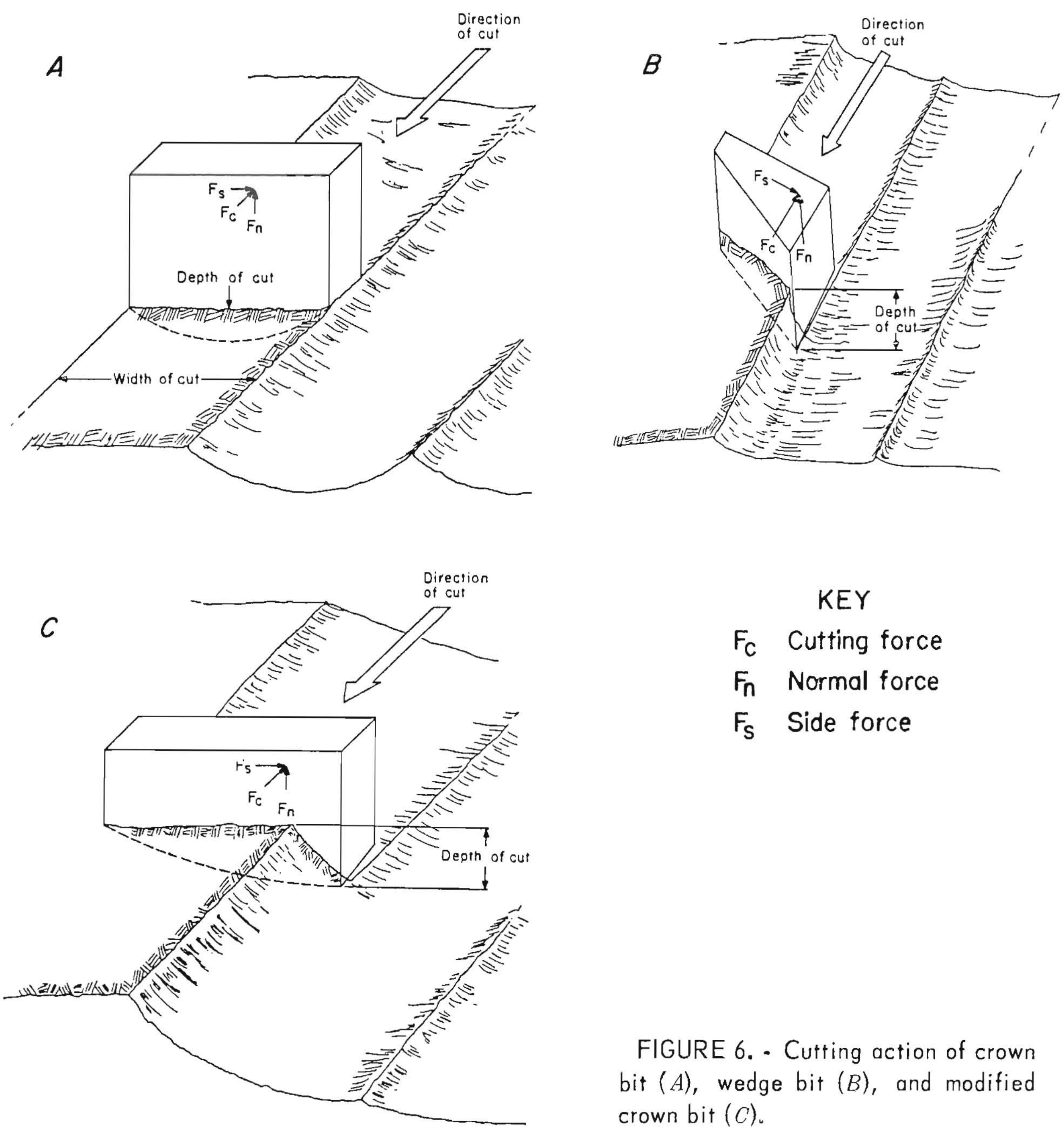

FIGURE 6. - Cutting action of crown bit (*A*), wedge bit (*B*), and modified crown bit (*C*).

cutting method is unique in both achieving high energy efficiency and having the ability to cut harder rocks. Higher efficiency cutting will ultimately result in mining machines that are less expensive to build and to operate. Since no single bit type is optimum in every rock type, the selection of the best bit in the field will necessarily be a trial-and-error process. However, because bit inserts are easily changed with the ripper cutting method, this is not expected to be a problem in the field.

The reason one bit shape is more efficient than another in certain rock types is not known at this time. However, it is fundamentally related to the ease or difficulty of forming and driving fractures ahead of the bit that ultimately form rock chips. While no sieve analysis of rock cuttings was conducted, it was generally observed that the most

TABLE 4. - Effect of bit shape on cutting efficiency[1]

(Cut width = 3 in, cut depth = 1 in)

Rock and bit type	Average cutting force, lb	Peak cutting force, lb	Specific energy, (in•lb)/in^3	Rock number (N_R)
Indiana limestone:				
Crown bit, +10° rake....	2,627	5,783	876	11.4
Wedge bit...............	2,500	4,000	834	12.0
Modified crown, 0° rake.	2,353	5,318	784	12.7
Kasota stone:				
Crown bit, +10° rake....	4,132	8,430	1,377	9.4
Wedge bit...............	5,903	11,444	1,968	6.6
Tennessee marble:				
Crown bit, +10° rake....	7,404	16,066	2,468	6.9
Wedge bit...............	5,640	10,727	1,880	9.0
Valders white rock:				
Crown bit, +10° rake....	4,771	NA	2,385	11.3

NA Not available. [1]Raw data are given in appendix table A-1.

TABLE 5. - Effect of rake angle on cutting efficiency[1]

Rock and bit rake angle	Average cutting force, lb	Specific energy, (in•lb)/in^3	Rock number (N_R)
Indiana limestone:[2]			
-10°.................	3,579	1,193	8.4
+10°.................	2,627	876	11.4
Valders white rock:[3]			
-10°.................	7,375	3,688	7.3
0°...................	6,215	3,107	8.7
+10°.................	4,771	2,385	11.3

[1]All tests conducted with crown bit. Raw data are given in appendix table A-2.
[2]Cut depth = 1 in, cut width = 3 in.
[3]Cut depth = 1 in, cut width = 2 in.

efficient bits always formed a larger proportion of large chips and a smaller volume of fines and dust. (The initiation and extension of fractures ahead of a drag cutter is the subject of a current Bureau research program, the results of which will be published in a future report.)

Besides cutting forces and energy consumption, the amount of dust generated and the wear on the bits were also closely observed. However, there was no significant dust generation or bit wear throughout the test program. This lack of observable dust and bit wear was considered to be a very favorable sign, but the cumulative test footage of approximately 200 ft was insufficient to draw any form conclusions.

RAKE ANGLE EXPERIMENTS

A second series of experiments was conducted to determine the effect of the bit rake angle on cutting force and cutting efficiency. Rake angles of -10°, 0°, and +10° were chosen for testing, since these represent the most likely range of angles that would be used in the field. The tests were conducted only with the crown bit and only in two rock types, but the results are expected to apply to other bit types and rock types as well. The results (table 5) show a steady improvement in performance as the rake angle goes from a negative to a positive value. The data show the positive rake angle bit to be 54 pct more efficient in Valders white rock and 35 pct more efficient in

Indiana limestone than the negative rake angle bit. This behavior is generally confirmed by other researchers working with similar bits and rock types (3, 6).

While the positive rake angle bit is usually the most efficient bit, in some situations a negative rake angle is chosen because of its superior wear resistance. The selection of the best rake angle is, therefore, a compromise between efficiency and wear resistance and will in general be different for each application. Again, ripper cutting lends itself to this trial-and-error selection process since bits can be changed quickly and easily in the field.

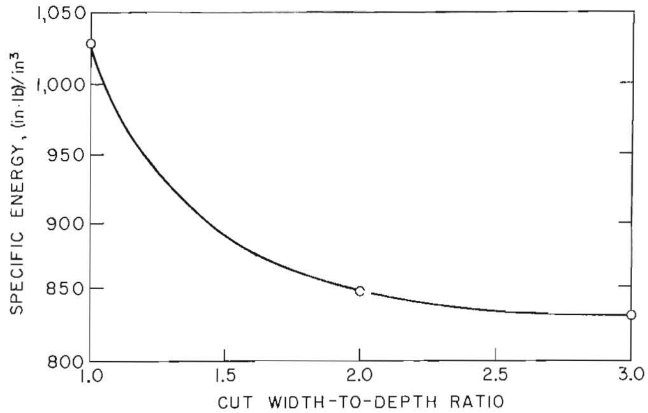

FIGURE 7. - Specific energy versus cut width-to-depth ratio for wedge bit in Indiana limestone.

CUT WIDTH AND CUT DEPTH EXPERIMENTS

It is well known that changing either the depth of cut or the width of cut produces a corresponding change in cutting forces and cutting efficiency. Most researchers report a linear or near linear response of cutting forces to changes in either the width or depth of cut. In addition, it is also known that an optimum depth of cut to spacing between cuts exists, where the efficiency of the process is maximum. The following experiment was conducted, therefore, to determine the cutting efficiency as a function of the width-to-depth ratio (W/D).

The experiments were conducted with two bit types, and the W/D was varied from 1.0 to 6.0. The results of these experiments are shown in table 6. For both bits tested, the most efficient operating point occurred at a W/D of 3. The plot of specific energy versus W/D for the wedge bit (fig. 7) shows that the optimum point is not sharply defined but rather is a range starting at about 2.0. Likewise, an analysis of the data for the modified crown bit shows efficient cutting with a W/D from 1.5 to 3.0. While the data are insufficient to define the exact optimum point, they do point out that high efficiency operation for both bits will begin at width-to-depth ratios of between 1.5 and 2.

The data also show that the optimum W/D values for efficient cutting depend on

TABLE 6. - Effect of cut width-to-depth ratio on cutting efficiency[1]

Bit type and width-to-depth ratio	Average cutting force, lb	Specific energy, (in·lb)/in³	Rock number (N_R)
Wedge bit:[2]			
W/D = 1.............	1,029	1,028	9.7
W/D = 2.............	1,698	849	11.7
W/D = 3.............	2,500	834	12.0
Modified crown bit:[3]			
W/D = 1.5...........	4,832	805	12.3
W/D = 3.............	2,353	784	12.7
W/D = 6.............	1,625	1,084	9.2

[1]All tests conducted in Indiana limestone. Raw data are given in appendix table A-3.

[2]Width-to-depth ratio based on constant 1-in cut depth and cut widths of 1, 2, and 3 in.

[3]Width-to-depth ratio based on constant 3-in cut width and cut depths of 2, 1, and 1/2 in.

both the rock cut and the bit type used. Therefore, determining the best W/D value to use will be an experimental process and may be unique for each specific application. The W/D is easily varied in the field by simply varying either the width or the depth of the cut.

BIT SIZE EXPERIMENTS

To determine how the forces and specific energy would vary for large-size ripper bits, a series of tests was conducted with a 6-in-wide, 0° rake crown bit. The crown bit was chosen for convenience as it did not require the fabrication of a new bit holder. The results obtained apply only to crown bits, but it is assumed that the scaling factor is of a similar nature for the wedge and modified crown bits. The depth of cut for the 6-in bit had to be held at 1 in instead of the 2 in that a W/D = 3 ratio would indicate. Again, this was necessitated by equipment limitations and would yield a W/D of 6. The results of the 6-in bit tests are shown in table 7, compared with results of the 3-in bit tests.

The 6-in-wide bit was found to be 10 pct more energy efficient in Indiana limestone and 13 pct more efficient in Tennessee marble. This result is impressive because the 6-in bit had the 0° rake angle and was run at W/D = 6 in comparison with the 3-in bit, which had a +10° rake angle and was run at W/D = 3. Thus, in a more direct comparison, the larger bit could be expected to achieve even higher gains in energy efficiency.

TABLE 7. - Effect of bit size on cutting efficiency[1]

Rock and bit size	Specific energy, $(in\cdot lb)/in^3$
Indiana limestone:	
3-in bit[2]............	876
6-in bit[3]............	790
Tennessee marble:	
3-in bit[2]............	2,468
6-in bit[3]............	2,150

[1]All tests conducted with crown bit. Raw data are given in appendix table A-4.
[2]+10° rake; W/D = 3.
[3]0° rake; W/D = 6.

The reason for the increased energy efficiency of larger bits is thought to be the larger volume of large chips formed and the smaller amount of dust produced and/or the possibility that a large volume of rock contains more favorable flaws, which makes it an inherently weaker mass. While the exact reason for the effectiveness of large bits is unknown, it is an important phenomenon and should be exploited as much as possible during rock cutting.

SUMMARY AND CONCLUSIONS

The cutting experiments conducted under this program have shown that ripper cutting can cut a wide variety of rock types and the energy efficiency of the process is high.

The experimental results can be summarized as follows:

1. Ripper cutting has been shown to be capable of cutting a wide variety of rocks ranging in strength from 10,000 to 27,000 lb/in^2.
2. Ripper cutting has achieved greater cutting efficiency than either tunnel-boring machines or roadheader machines.
3. All of the bit shapes tested achieved high-efficiency cutting, but not every bit achieved high efficiency in every rock type. Therefore, the selection of the optimum bit shape for a given rock type is a trial-and-error process.
4. The bits with positive rake angles required 25 to 35 pct less energy to fragment rock than did the bits with negative rake angles.
5. The most energy-efficient operating range for the bits tested began at a cut width-to-depth ratio of between 1.5 and 2.
6. The efficiency of the cutting process increased as the size of the bit increased from 3 to 6 in.
7. The ripper cutting process produces only a small amount of airborne dust during fragmentation.

REFERENCES

1. Concha, E., and J. A. Bartol. Study of Automated Continuous Explosive Excavation Systems (contract J010082, Appl. Eng. Res., Inc.). BuMines OFR 78-83, 1982, 93 pp.; NTIS PB 83-196212.

2. Gaye, F. Efficient Excavation With Particular Reference to Cutting Head Design of Hard Rock Machines. Tunnels and Tunnelling, 1972, pt. 1, Jan., pp. 39-48; pt. 2, Mar., pp. 135-143.

3. Hignett, H. J., R. A. Snowdon, and J. Temporal. Rock Cutting Trials in Lower Chalk. Paper in 18th U.S. Symposium on Rock Mechanics (Keystone, CO, June 22-24, 1977). CO School of Mines, Golden, CO, 1977, 34 pp.

4. Hughes, H. M. Some Aspects of Rock Machining. J. Rock Mech. and Min. Sci., v. 9, 1972, pp. 205-211.

5. Morrell, R. J., and R. J. Wilson. Toward Development of a Hard-Rock Mining Machine--Drag Cutter Experiments in Hard, Abrasive Rocks. BuMines RI 8784, 1983, 19 pp.

6. Roxborough, F. F., and A. Rispin. The Mechanical Cutting Characteristics of the Lower Chalk. Tunnels and Tunnelling, Jan. 1973, pp. 45-67.

APPENDIX A.--TEST DATA

TABLE A-1. - Test results on bit shape (raw data for table 4)

(Cut width = 3 in, cut depth = 1 in)

Rock and bit type	Individual cutting force, lb
Indiana limestone:	
Crown bit, +10° rake	2,384
	2,805
	2,805
	2,530
	3,650
	2,805
	2,450
	2,450
	2,082
	2,450
	2,450
Average...........	2,627
Wedge bit...........	2,110
	2,260
	2,718
	2,714
	2,710
Average...........	2,500
Modified crown, 0° rake...............	2,352
	2,352
	2,352
	2,646
	2,058
Average...........	2,353
Kasota stone:	
Crown bit, +10° rake	3,305
	4,808
	3,907
	3,305
	3,907
	3,606
	3,822
	4,998
	4,410
	4,704
	4,704
	4,116
Average...........	4,132
Wedge bit...........	6,497
	5,933
	5,368
	5,791
Kasota stone--Con.	
Wedge bit--Con......	5,933
	4,802
	7,062
	6,215
	5,650
	6,215
	6,215
	5,156
Average...........	5,903
Tennessee marble:	
Crown bit, +10° rake	7,838
	7,125
	7,801
	7,125
	7,140
	7,125
Average...........	7,404
Wedge bit...........	4,824
	6,030
	5,126
	6,030
	4,825
	6,633
	5,900
	5,900
	6,490
	6,195
	4,720
	5,015
Average...........	5,640
Valders white rock:	
Crown bit, +10° rake	1,705
	5,891
	3,646
	3,927
	5,610
	5,891
	4,488
	5,610
	6,171
Average...........	4,771

TABLE A-2. - Test results on rake angle (raw data for table 5)[1]

Rock and bit rake angle	Individual cutting force, lb
Indiana limestone:[2]	
-10°	2,950
	4,720
	3,520
	3,257
	3,540
	2,950
	2,950
	3,770
	4,350
	3,480
	4,350
	3,770
	2,900
Average	3,579
+10°	2,384
	2,805
	2,805
	2,530
	3,650
	2,805
	2,450
	2,450
	2,082
	2,450
	2,450
Average	2,627

Rock and bit rake angle	Individual cutting force, lb
Valders white rock:[3]	
-10°	6,671
	9,040
	6,520
	8,300
	7,700
	7,700
	8,154
	3,261
	7,412
	9,330
	8,451
	7,110
	6,220
Average	7,375
0°	4,189
	6,270
	6,270
	7,410
	6,270
	6,270
	7,125
	6,412
	6,698
	6,555
	5,180
	5,985
Average	6,215
+10°	1,705
	5,892
	3,646
	3,927
	5,610
	5,891
	4,488
	5,610
	6,171
Average	4,771

[1]All tests conducted with 3-in wide crown bit.
[2]Cut depth = 1 in, cut width = 3 in.
[3]Cut depth = 1 in, cut width = 2 in.

TABLE A-3. - Test results on cut width-to-depth ratio (raw data for table 6)[1]

Bit type and width-to-depth ratio	Individual cutting force, lb	Bit type and width-to-depth ratio	Individual cutting force, lb
Wedge bit:[2]		Modified crown bit:[3]	
W/D = 1..............	900	W/D = 1.5............	5,520
	1,200		3,588
	1,300		4,968
	1,300		4,968
	700		3,588
	700		6,348
	1,300		4,832
	850	W/D = 3..............	2,353
	1,029		2,353
W/D = 2..............	1,805		2,353
	2,100		2,647
	2,000		2,059
	1,450		2,353
	1,740	W/D = 6..............	1,728
	1,600		1,728
	1,750		1,728
	1,150		1,584
	1,698		1,440
W/D = 3..............	2,111		1,728
	2,260		1,440
	2,710		1,625
	2,710		
	2,710		
	2,498		

[1]All tests conducted in Indiana limestone.
[2]Width-to-depth ratio based on constant 1-in cut depth and cut widths of 1, 2, and 3 in.
[3]Width-to-depth ratio based on constant 3-in cut width and cut depths of 2, 1, and 1/2 in.

TABLE A-4. - Test results on bit size (raw data for table 7)[1]

Rock and bit size	Value	Rock and bit size	Value
Indiana limestone:[3]		Tennessee marble:	
3-in bit:[2]		3-in bit:[2]	
Individual cutting force....lb..	2,384	Individual cutting force....lb..	7,838
	2,805		7,125
	2,805		7,801
	2,530		7,125
	3,650		7,410
	2,805		7,125
	2,450	Average......................	7,404
	2,450	Specific energy....(in·lb)/in^3..	2,468
	2,082	6-in bit:[3]	
	2,450	Individual cutting force....lb..	11,140
	2,450		13,647
Average......................	2,627		13,925
Specific energy....(in·lb)/in^3..	876	Average......................	12,904
6-in bit:[3]		Specific energy....(in·lb)/in^3..	2,150
Individual cutting force....lb..	4,565		
	4,564		
	5,101		
Average......................	4,743		
Specific energy....(in·lb)/in^3..	790		

[1]All tests conducted with crown bit.
[2]+10° rake; W/D = 3. [3]0° rake; W/D = 6.

APPENDIX B.--FUTURE TESTING

Because of the success of this study, the decision was made to develop the ripper cutting concept into a full-scale rock fragmentation system for further study, to determine if a vaible fragmentation system could be devised using the ripper cutting method.

The general concept of such a ripper fragmentation system is shown in figure 1 in the main text. Note the curvilinear cutting paths formed by a single large bit that starts at zero depth, gradually deepens to a maximum at the midpoint, and then exits again at zero depth. As the cutting arm is rotated horizontally after each cut, it forms an opening of generally rectangular shape. This represents the general configuration of the ripper fragmentation system.

To test this theoretical system in the laboratory, a ripper system test device was designed that would allow actual full-scale testing of the ripper system to determine its ability to excavate an opening in a solid rock mass and to determine its production rate and energy requirements. The ripper tester fabricated for this test program is shown in figure B-1. This tester mounts a single 9- to 12-in-wide drag bit and can cut an opening approximately 6 by 6 ft. The tester can generate 150,000 lb of cutting force and a cutting speed of 6 in/s.

This ripper tester has already successfully cut high-strength concrete in the laboratory during preliminary trials. The results of this work will be published in a future Bureau report.

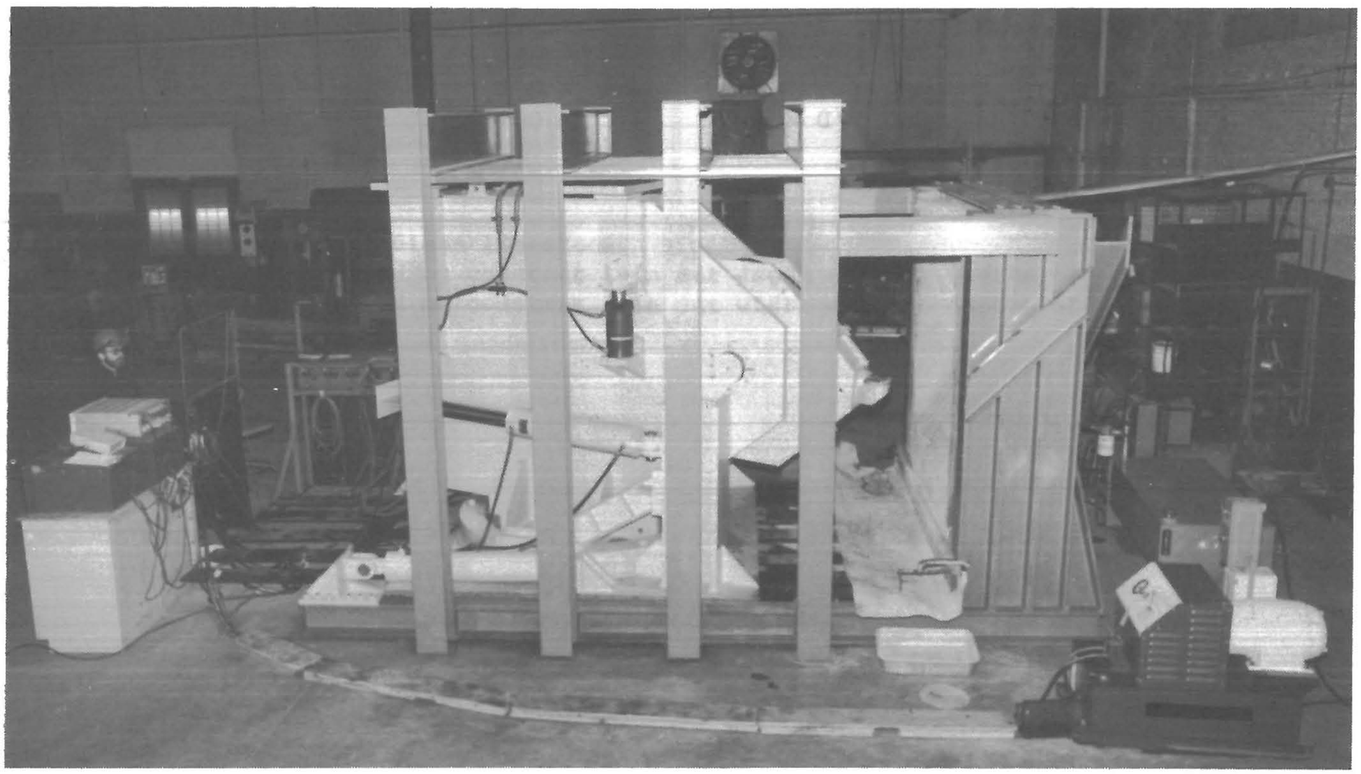

FIGURE B-1. - Full-scale ripper fragmentation system tester.